University of Ottawa

Sensor Networks: Research Challenges in Practical Implementations, Physical Characteristics and Applications

Rami Abielmona (rabielmo@site.uottawa.ca)
Ph.D. Candidate
Sensing and Modeling Research Lab (SMRLab)
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School of Information Technology and Engineering (SITE)

Outline

- What are sensor networks (SNETs) ?
- Brief history of SNETs
- SNET taxonomies
  - Hardware realizations
  - Transmission media
  - Power consumption valuations
  - Communication architectures
- SNODE physical characteristics
  - Sensor types and characteristics
  - Processor support
  - Operating system support
  - Wireless technologies
- SNET practical implementations
  - SensIT Program (DARPA research)
  - Smart Dust Project (UC Berkeley research)
  - Intelligent Sensor Agents (SMRLab research)
- Research directions
- Market trends / potential applications
- Conclusions

What are sensor networks ?

- Sensor networks (**SNETs**) are composed of multiple interconnected and distributed sensors that collect information on areas or objects of interest
- Sensor nodes (**SNODEs**) make up each sensor network and consist of three major components:
  - Parameter, event and object **sensing**
  - Data **processing** and classification
  - Data **communications**
- SNETs can be applied to a myriad of areas:
  - Military (e.g. object tracking)
  - Health (e.g. vital sign monitoring)
  - Environment (e.g. natural habitat analysis)
  - Home (e.g. motion detection)
  - Manufacturing (e.g. assembly line fault-detection)
  - Entertainment (e.g. virtual gaming)
  - Digital lifestyle (e.g. parking spot tracking)

Design for what ?

- **Large number of sensors**
  - Fault-tolerance and scalability are major design factors
  - Clustering is a potential solution to the complexity issue
- **Low energy utilization**
  - Power-aware protocols and algorithms are being researched
  - Could use energy-scavengers such as solar cells
- **Network self-organization and discovery**
  - SNODEs have a high turnover ratio but the SNET does not
  - Each SNODE needs to know its absolute, or at least relative, position, as well as its neighbour's locations
- **Collaborative signal processing**
  - Data fusion is utilized to detect, track and/or classify objects of interest (information processing)
- **Tasking and querying abilities**
  - Data-centric vs. address-centric techniques
- **Data aggregation and dissemination**
  - Aggregation involves transforming data to information, while dissemination involves acquiring data from the SNODEs

Sensor networks vs. mobile ad-hoc networks (MANETs)

SNETs	MANETs
SNODEs may not have a global identification	Each node has a global identification
Mainly utilizes broadcast communications	Mainly utilizes point-to-point communications
Number of nodes is relatively high	Number of nodes is relatively low
Limited in power, computational capacity and memory	*Unlimited* in power, computational capacity and memory
Topology changes frequently	Topology is dynamic
Low-level radio frequency communications (AM/FM)	Bluetooth, 802.11 and ultrawideband (UWB)
Flooding and gossiping communication protocols	TCP (UDP) / IP communication protocols

Table 1. SNETs vs. MANETs

SNET Chronology (1)

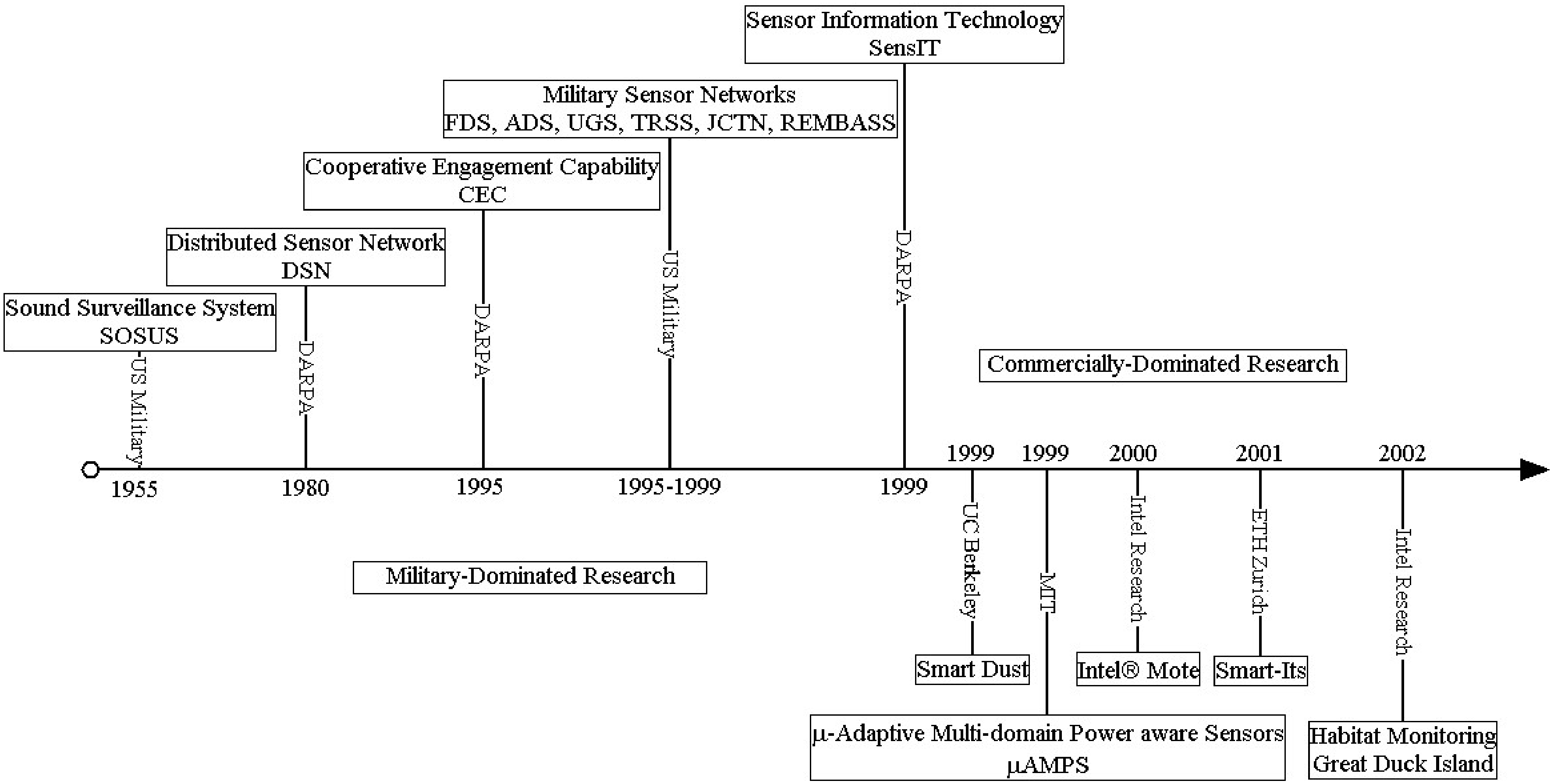


Figure 1. SNET chronology

SNET Chronology (2)

- Sound Surveillance System (SOSUS) [1]
  - US military initiative in 1950s
  - System of acoustic sensors at the bottom of the ocean used to detect quiet Soviet submarines
- Distributed Sensor Network (DSN) [2]
  - DARPA research project in1980
  - Built on top of acoustic sensors with a
    - Resource-sharing network communication
    - Processing techniques and algorithms
    - Distributed software
- Cooperative Engagement Capability (CEC) [3,4]
  - DARPA research project in 1995
  - Summoned the *network-centric warfare* era, where the sensors belong to shooters rather than weapons (*platform-centric warfare*)
  - Goal was to provide a "common operating picture" imperative for distributed military operations
- Military Sensor Networks (FDS, ADS, JCTN, …) [5]
  - FDS – Fixed Distributed System → Antisubmarine warfare
  - ADS – Advanced Deployable System → Antisubmarine warfare
  - JCTN – Joint Composite Tracking Network → Integrated air picture
- Sensor Information Technology (SensIT) [6]
  - DARPA research program started in 1999
  - Developed new networking techniques that could be used in hostile environments
  - Developed networked information processing (extract information from SNET data)

SNET Chronology (3)

- Smart Dust Project [7]
  - UC Berkeley research project in 1999
  - Main goal is miniaturization
    - Sensing and communication co-exist in a cubic millimeter package
    - Sub-goals include integration and energy management
  - Has spawned off many different projects including TinyOS and the Intel Mote projects
- µAMPS Project [8]
  - MIT research initiative in 1999
  - Objective is the signal and power conditioning, filtering and communication
  - Less emphasis is placed on the sensing unit (black box)
  - Completed in 2002 and spawned into µAMPS-II (SoC package)
- Intel® Mote Project [9]
  - Intel Research initiative in 2000
  - Builds upon the Smart Dust project
  - Attempt to build a universal embedded node platform for SNETs
- Smart-Its Project [10]
  - ETH Zurich research project started in 2001
  - Analogy is made to *Post-It notes*, but using radio tags
  - Will attach to everyday items to give them new interaction patterns and behaviors
- Habitat Monitoring Project [11]
  - Intel Research Laboratory at Berkeley collaboration started in 2002
  - SNODEs are burrowed under the ground and form a wireless SNET
  - Used to non-intrusively monitor the natural habitat of sensitive wildlife (e.g. seabirds)

SNET Taxonomies (1)

- Hardware realization
  - Three main components re-appear
    - Sensing unit
    - Processing unit
    - Communications unit
  - SNODE must
    - Consume very little power
    - Be autonomous and low-cost
    - Adapt easily to the environment
    - Fit into small packaging

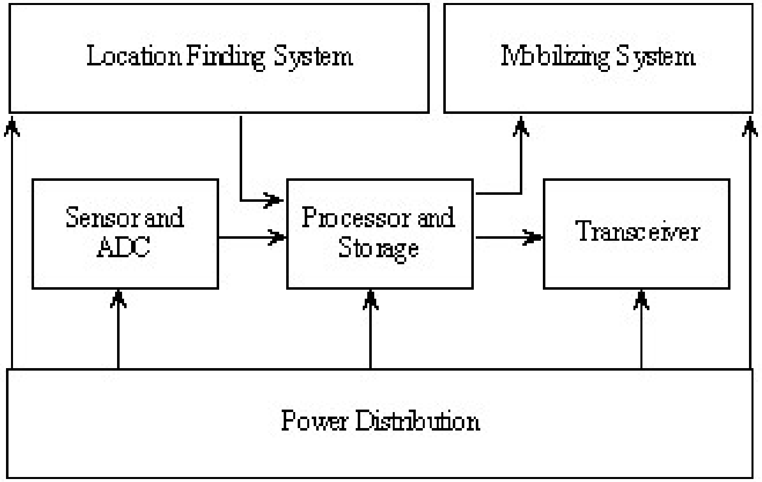


Figure 2. SNODE internal components Adapted from [5]

- Today's system-on-chip (SoC) packages allow for integrated functionalities to reside on the same chip (e.g. rfPIC)
  - RF transceiver
    - Data rates are very low
    - Packets are very small
    - Frequency re-use is very high
  - Processor and core memory
    - Small and fast processors
    - ROM and RAM cores
    - Small-footprint RTOS (e.g. TinyOS)

SNET Taxonomies (2)

- Transmission media
  - Radio, infrared or optical media are viable
  - IR forces the SNODEs to have line-of-sight (LOS) capabilities which are very inefficient in SNETs
  - Optical media forces the SNET to be interconnected using an optical fibre, resulting in an obtrusive invasion upon the environment
  - Radio frequency (RF) media is the most suitable
    - Standards are becoming available worldwide
    - Freely licensable bands (i.e. ISM)
    - Transceivers are becoming smaller in size, cheaper in cost and lower in power consumption
    - RF cores can be built right onto the processing unit!

SNET Taxonomies (3)

- Power consumption valuations
  - Sensing unit power factors
    - Depends on the application (e.g. temperature sensing will consume less power than visual object detection)
    - Could be lowered by turning off the sensing unit whenever possible
  - Processing unit power factors [5]
    - $P_P = CV_{dd}^2 f + V_{dd} I_0 e^{V_{dd}/nV_T}$ → Due to leakage current
    - "Energy cost of transmitting 1 KB a distance of 100 m is approximately the same as that for executing 3 million instructions by a 100 MIPS processor"!!
    - Power saving techniques include dynamic voltage scaling, operating frequency reductions and smaller transistors (hence lower capacitance)
  - Communications unit power factors [5]
    - $P_c = N_T[P_T(T_{on} + T_{st}) + P_{out}(T_{on})] + N_R[P_R(R_{on} + R_{st})]$
    - Start-up time (T_{st}) is non-negligible for RF transceivers, thus it is inefficient to turn the latter on and off
    - Main static power consumption parameter of the SNODE
  - Novel techniques have to balance computation and communication

SNET Taxonomies (4)

- Communication architectures
  - Left figure indicates a hierarchical (military-style) communication scheme
  - Right figure indicates a peer-to-peer scheme

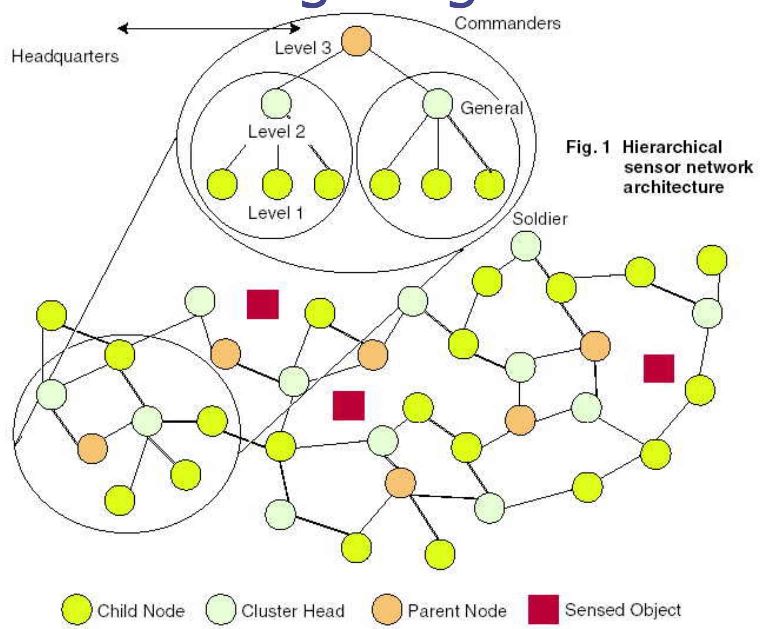


Figure 3. SNET sample comm. architecture Reproduced from [13]

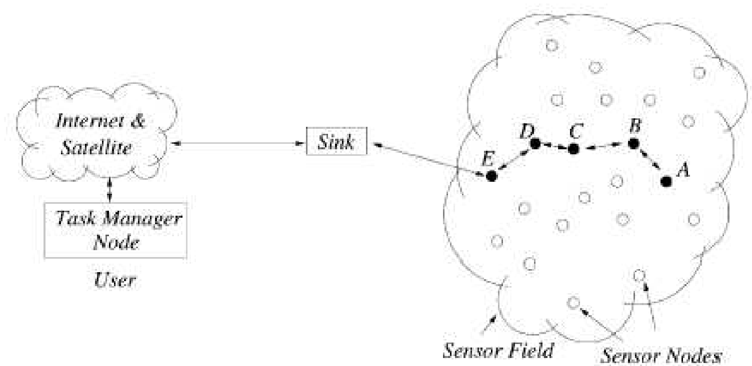


Figure 4. SNET sample comm. architecture Reproduced from [5]

SNET Taxonomies (5)

- Communication architectures
  - In either scheme, each SNODE is capable of collecting data, locally processing it and sending it to its neighbors/commanders
  - A protocol stack is present on each SNODE (will be discussed in more detail in Dr. Stojmenovic's presentation)
    - Application layer
      - Depends on the overall task being accomplished
    - Transport layer
      - Aids in data flow control throughout the SNET
    - Network layer
      - Involves routing the data amongst the SNODEs and out the SNET
    - Data link layer
      - Ensures reliable communication connections between SNODEs
    - Physical layer
      - Encapsulates the modulation, transmission and reception of data

SNODE Physical Characteristics (1)

- *Sensor types and characteristics* [14]
- What are some of the sensors that could be used in the field ?
  - **Tactile and proximity**
    - Tactile feelers, tactile bumpers or distributed surface areas
    - Capacitive, ultrasonic, microwave or optical proximity sensors
  - **Acoustical energy**
    - Sonar (sound navigation and ranging) sensors utilize the speed of propagation of sound waves traveling through the medium to calculate the time of flight from the sensor to the object of interest
    - Main advantages are
      - Very low cost and easy to interface to
      - Fairly wide dispersion angle increases probability of detection
      - Lambertian surfaces provide excellent reflection regardless of color
    - Main drawbacks are
      - Attenuated by atmospheric conditions
      - Target reflectivity is not always ideal
      - Disturbed by air turbulence and environment temperature

SNODE Physical Characteristics (2)

- **Optical (electromagnetic) energy**
  - Optical energy sensors (i.e. infrared and laser-based systems)
  - Main advantages are
    - Increased range of operation (due to narrow and collineated beam)
    - Reduced noise and interference
    - Fewer multipath problems
  - Main drawbacks are
    - Atmospheric absorption and scattering
    - Environment temperature greatly affects power output of LEDs
    - Index of refraction is a surface property of the object (i.e. variable)
- **Magnetic compasses and gyroscopes**
  - Former measures vehicle heading according to true north
  - Latter measures vehicle orientation by maintaining its balance
- **GPS**
  - Sensor employs TOF satellite-based trilateration in order to recover its 3-D position
  - It utilizes 4 different geostationary satellites in order to recover its absolute latitude, longitude, elevation and time synchronization

SNODE Physical Characteristics (3)

- **Environment sensors**
  - What else can we measure about our environment ?
    - Temperature
    - Light intensity
    - Smoke
    - Humidity
    - Pressure
    - Acoustical noise
    - Motion
    - Imaging/vision
    - Perspiration
    - Liquid levels
    - Weight/mass
    - Radiation
    - Short-term: smell, taste and time
    - Long-term: fear, hunger, anger, happiness, sadness and beauty
    - And what about knowledge, humour, innovation and intelligence ?

SNODE Physical Characteristics (4)

- *Processor support*
- The following characterize our ideal processor
  - Relatively fast execution times
  - Low power consumption and production cost
  - Small area footprint
  - On-chip memory (cache, ROM and/or RAM cores)
  - Abundance of I/O capabilities
  - Standard interfaces (serial, parallel, USB, …)
  - Robust instruction set architecture
  - Availability of development tools
  - Testable and reliable
  - Industrial and academic support!
- It is imperative to remember that this is a physical system that employs computer control for a specific purpose and not for general-purpose computation (i.e. embedded system)

SNODE Physical Characteristics (5)

Processor Family	Intel 8051 µC	Motorola 68HC11 µC	Motorola ColdFire µC	Motorola PowerPC µC	ARM µC	Atmel µC	Microchip µC
Processor architecture	RISC	CISC	CISC (MCF5407)	RISC (MPC5500)	RISC (ARM7)	RISC (AVR)	RISC (PIC)
Processor speed	12 MHz – 16 MHz	4 MHz	33 MHz - 333 MHz	Up to 300 MHz	50 MHz	Up to 16 MHz	Up to 40 MHz
ROM size	4 KB	8 KB – 12 KB	16 KB ICache, 8 KB DCache	4 MB Flash	40 KB – 192 KB Flash	Up to 128 KB Flash	Up to 512 bytes
RAM size	128 bytes	256 bytes – 512 bytes	4 KB SRAM	128 KB	4 KB SRAM	4 KB SRAM	Up to 368 bytes
I/O capabilities	4 8-bit ports	5 8-bit ports	16-bit ports	N/A	Up to 75 GPIO	Up to 53 GPIO	Up to 33 GPIO
Interfaces	UART	UART, SPI, ADC	UART, USART, I^{2}C	None	UART	UART, SPI	UART, USB, I^{2}C
Data bus width	8-bits	8-bit 6800 or 6809 µP	32-bit MFL5xxx µP	32-bit MPC55xx µP	32-bit ARM7 µP	8-bit megaAVR µP	8-bit PIC16 family
Particulars	2 16-bit counters/timers	512 bytes of EEPROM	2 16-bit timers	MMU and DSP functionality	8-bit ADC, timers, PWM and watchdog	4 KB EEPROM, 10-bit ADC, PWM	8-bit ADC, 8-bit timer, comparator

Table 2. Embedded processor comparison chart

SNODE Physical Characteristics (6)

- *Operating system support*
- The following characterize our ideal operating system
  - Multitasking and interrupt support
  - Vast language and microprocessor support
  - Ease of tool compatibility (compiler, assembler, …)
  - Wide array of services (queues, semaphores, timers, …)
  - Small area footprint (both program and data)
  - Scaleable design
  - Availability of debugging tools
  - Standards compatibility
  - Extensive device driver support
  - Industrial and academic support!
- It is imperative to have a low interrupt latency, to allow for reentrancy and to support pre-emptive scheduling, as all will help us meet our real-time constraints when dealing with SNODE computational requirements

SNODE Physical Characteristics (7)

RTOS	Mentor Graphics - Nucleus	Cygnus Solutions – eCos	Lynx Real-Time – LynxOS	Microsoft Corp. – Windows CE	QNX Software – QNX	UC Berkeley – TinyOS	Avocet Systems – AvSYS	Micrium – µC/OS-II
Target CPUs	68K, ARM, MIPS, x86, ColdFire, SPARC, H8, SH, TI DSPs	ARM, MIPS, MPC8xx, SPARC, Toshiba TX139	68K, MIPS< MPC8xx, x86, SPARC, PA-RISC	ARM , MIPS, PowerPC, SH, x86, Strong Arm, NEC	MIPS, MPC8xx, x86	Network processors	65816, 68HC08/11 /12/16, 8051, Z8, Z80, 6809/01/0 3	ARM, AVR, Nios, x86, PowerPC, StrongARM, PIC-18xx, MIPS, 68K, MicroBlaze, Z80
Languages supported	C, C++, Java	Assembly, C, C++	Ada, assembly, C, C++, Java, Fortan, Perl	Assembly, C, C++, Java	Assembly, C, C++, Java	nesC	C	C
ROM footprint	< 1 – Varies	< 1 – Varies	33 – 256	270 – 626	40 – Varies	3500	0.8 – 640	2048
RAM footprint	< 1 – Varies	< 1 – Varies	11 – 115	40 – 720	Varies	4500	0.8 – 640	200
Multitasking	Round robin, time slice, dynamic priorities	Round robin, time slice, fixed priorities	Round robin, time slice, fixed priorities	Round robin, time slice, dynamic priorities	Round robin, time slice, dynamic priorities	Priority scheduling	Time slice, fixed priorities	Round robin, time slice, fixed priorities
Licensing	Per license	Free	Per license	Per license	Per license	Free	Per license	Free for research
Particulars	POSIX, TCP/IP, source code	POSIX, TCP/IP, source code	POSIX, TCP/IP, source code	POSIX, TCP/IP, source code	POSIX, TCP/IP, source code	Event-based	POSIX, TCP/IP, source code	POSIX, TCP/IP, source code

Table 3. RTOS comparison chart – Adapted from [15]

SNODE Physical Characteristics (8)

- *Wireless technologies*
- The following characterize our ideal wireless technology
  - Imperative low power utilization
  - Simple transceiver circuitries
  - Resilient to multipath effects
  - Worldwide medium availability
  - Standards compatibility
  - Freely licensable
  - Medium to wide range of operation
  - Decent data transmission rate
  - Industrial and academic support!
- Due to the limited power supply, researchers are trying to combine all three components (sensing, processing and transceiver) into tiny, low-power, low-cost units

SNODE Physical Characteristics (9)

Wireless Technology	BlueTooth	IrDA	IEEE 802.15.3a Ultrawideband (UWB)	IEEE 802.11a	IEEE 802.11b (Wi-Fi)	IEEE 802.11g	IEEE 802.15.4 (ZigBee)
Data rate (Mb/s)	1-2	4	100-500	54	11	54	250 kbps and 20 kbps
Output power (mW)	100	100 mW/sr	1	40-800	200	65	30
Range (meters)	100	1-2	10	20	100	50	30
Frequency band	2.4 GHz	Infrared	3.1-10.6 GHz	5 GHz	2.4 GHz	2.4 GHz	2.4 GHz and 868/915 MHz
Comments	7 active nodes	Very short-range	Low power, short-range applications	Wireless LANs with high data rate	Wireless LANs with low data rate	Wireless LANs with lower power	Low duty-cycle applications

Table 4. Wireless technologies comparison chart – Adapted from [16]

SNET Practical Implementation #1

- *SensIT program at DARPA [12]*
- There are two main objectives to the program
  - To develop novel networking techniques for SNETs deployed in unstructured and sometimes hostile environments
  - To develop network information processing procedures, so as to extract useful, reliable and timely information from the SNET
- Data-centric routing focuses on the data generated by the sensors themselves, and avoids the overhead of assigning unique addresses to each SNODE
- The SNODEs are supposed to reach a networked consensus, when it comes to the application at hand (e.g. classification of a target)
- SensIT networks are interactive and can be dynamically tasked and queried by human operators, using a query/tasking language
- Multiple simultaneous users are allowed in the system
- Main four functions of SensIT are: detection, identification, location and tracking of objects

SNET Practical Implementation #1

- Deployed the following equipment in the field
  - 29 Palms
  - 10 different armoured vehicles classified under 3 types
  - Data analysis machines
  - Various acoustic and seismic sensors organized in SNETs
- Goal was to classify each vehicle passing between two checkpoints using the gathered SNODE data
- Results were extremely good, except when a large number of vehicles or vehicles of various types were within the convoy
- Three different techniques were studied
  - Collaboration between 1 SNODE
  - Collaboration between 2 SNODEs within target field of view
  - Collaboration between 2 SNODEs not within target field of view ← Winner

Figure 5. SensIT scenario run-through
Reproduced from [17]

SNET Practical Implementation #2

- *Smart Dust research project at UC Berkeley*
- Also sometimes referred to as dust motes (small particle)
- There is one main objective of this project
  - Miniaturization!
  - The sub-units are to fit in a cubic millimeter
- There have been many variations of dust motes over the years

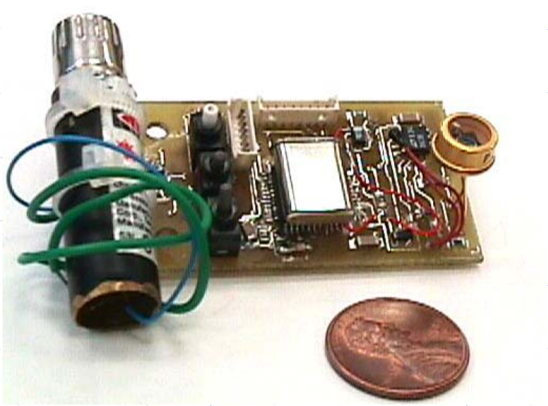
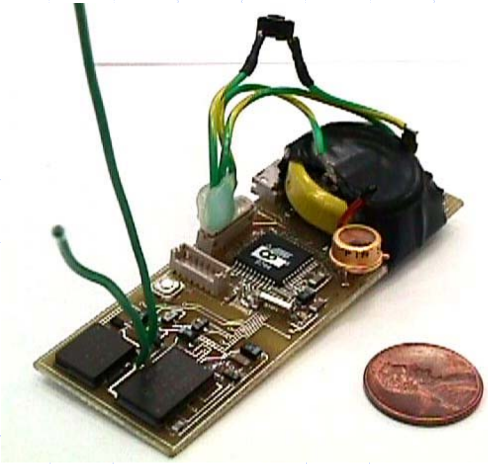


Figure 6. Laser mote
Reproduced from [18]

Figure 7. RF mote
Reproduced from [18]



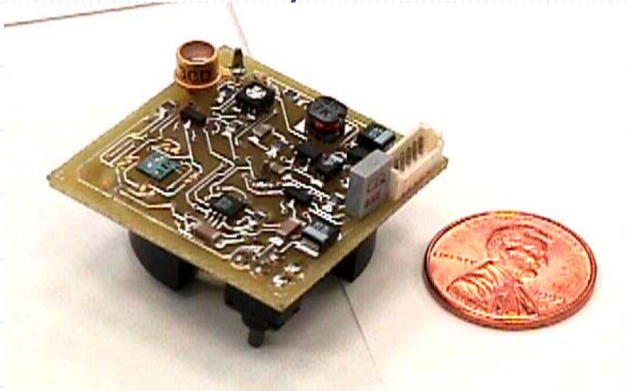
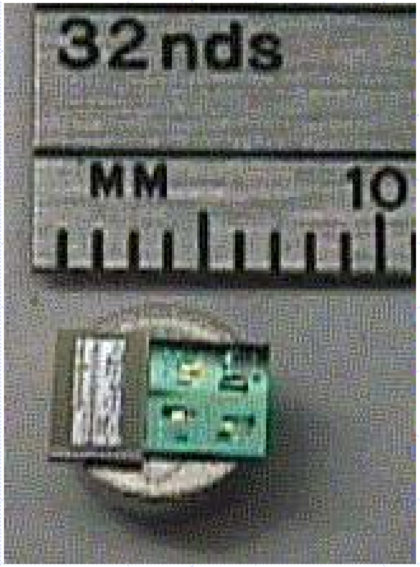


Figure 8. MEMS optical mote
Reproduced from [18]

SNET Practical Implementation #2



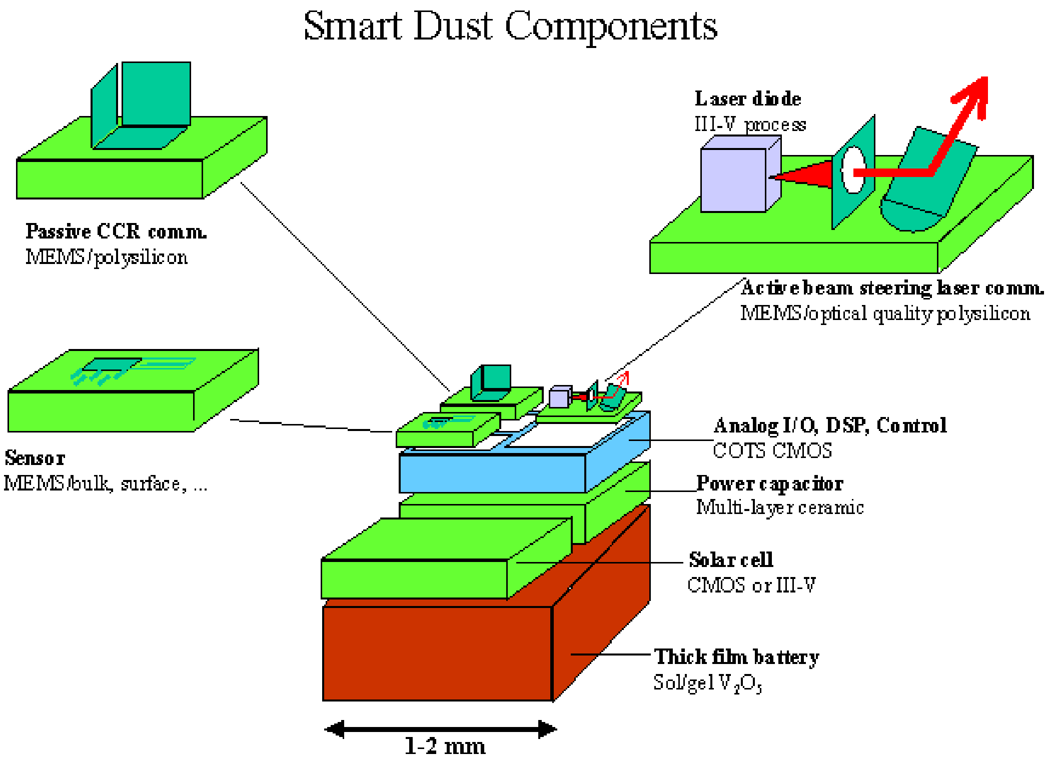


Figure 9. July 1999 mote
Reproduced from [19]

Figure 10. Ideal mote
Reproduced from [19]

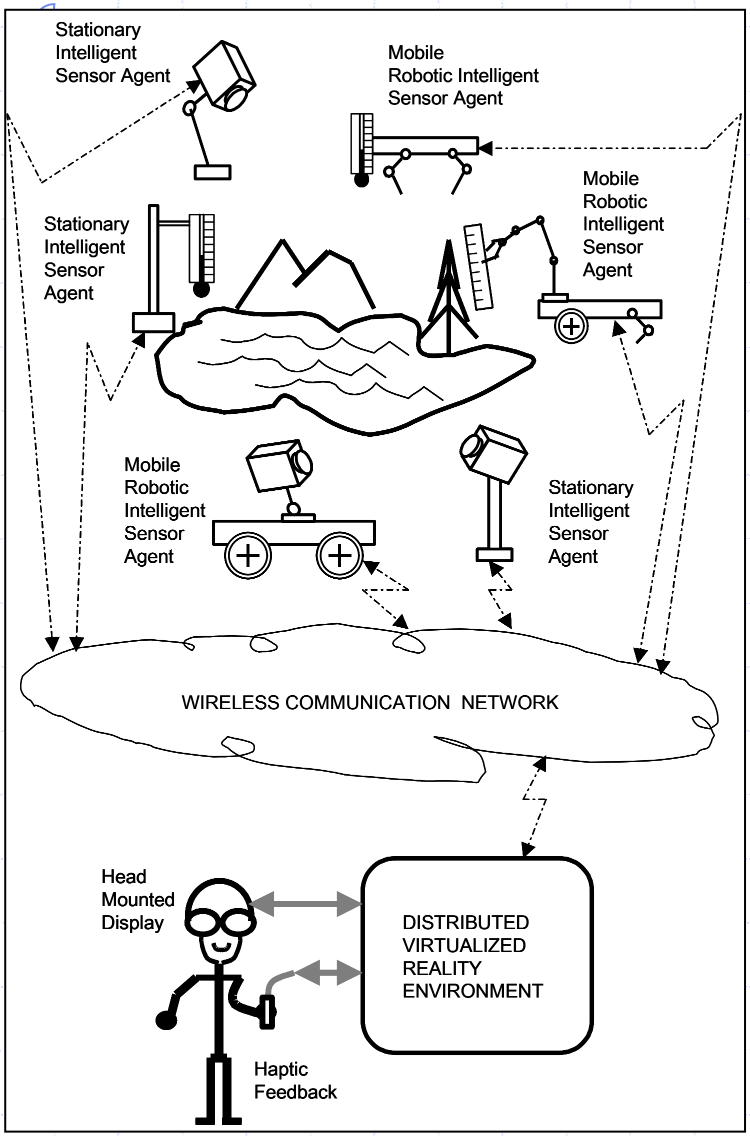
SNET Practical Implementation #3

- *Intelligent Sensor Agent (ISA) research project at SITE (University of Ottawa) started in 2002*
- Environments range from the natural to the scientific to the military and even to the underwater
- There are many parameters to keep track of, and each parameter exhibits complex behavior. For example:
  - Chemical substances can be very tough to sense
  - Sensors deployed in enemy territory could be destroyed
- The motivations are:
  - Development of a new generation of autonomous wireless *Robotic Intelligent Sensor Agents (R-ISAs)* for complex environment monitoring
  - Fusion of collected sensor data into a world model which is remotely available to human monitors
  - Representation of the model in an interactive *Virtualized Reality Environment*
- The overall goal is to allow the human operator to remotely and continuously monitor the behavior of the environment and to actuate upon some of its constituents, if the need arises

SNET Practical Implementation #3

- There are many environmental properties [20]
  - Accessible vs. inaccessible
    - If accessible: can obtain complete and accurate information about environment
  - Deterministic vs. non-deterministic
    - If deterministic: can guarantee that a single action has a known effect on the environment
  - Episodic vs. non-episodic
    - If episodic: can link performance of the robot to a discrete set of episodes occurring in the environment
  - Static vs. dynamic
    - If static: can assume that environment does not change, unless it is from an action of a robot/agent
  - Discrete vs. continuous
    - If discrete: can represent the environment with a fixed and finite number of actions and perceptions
- Most complex type of environment is the real world because it is inaccessible, non-deterministic, non-episodic, dynamic AND continuous!

SNET Practical Implementation #3

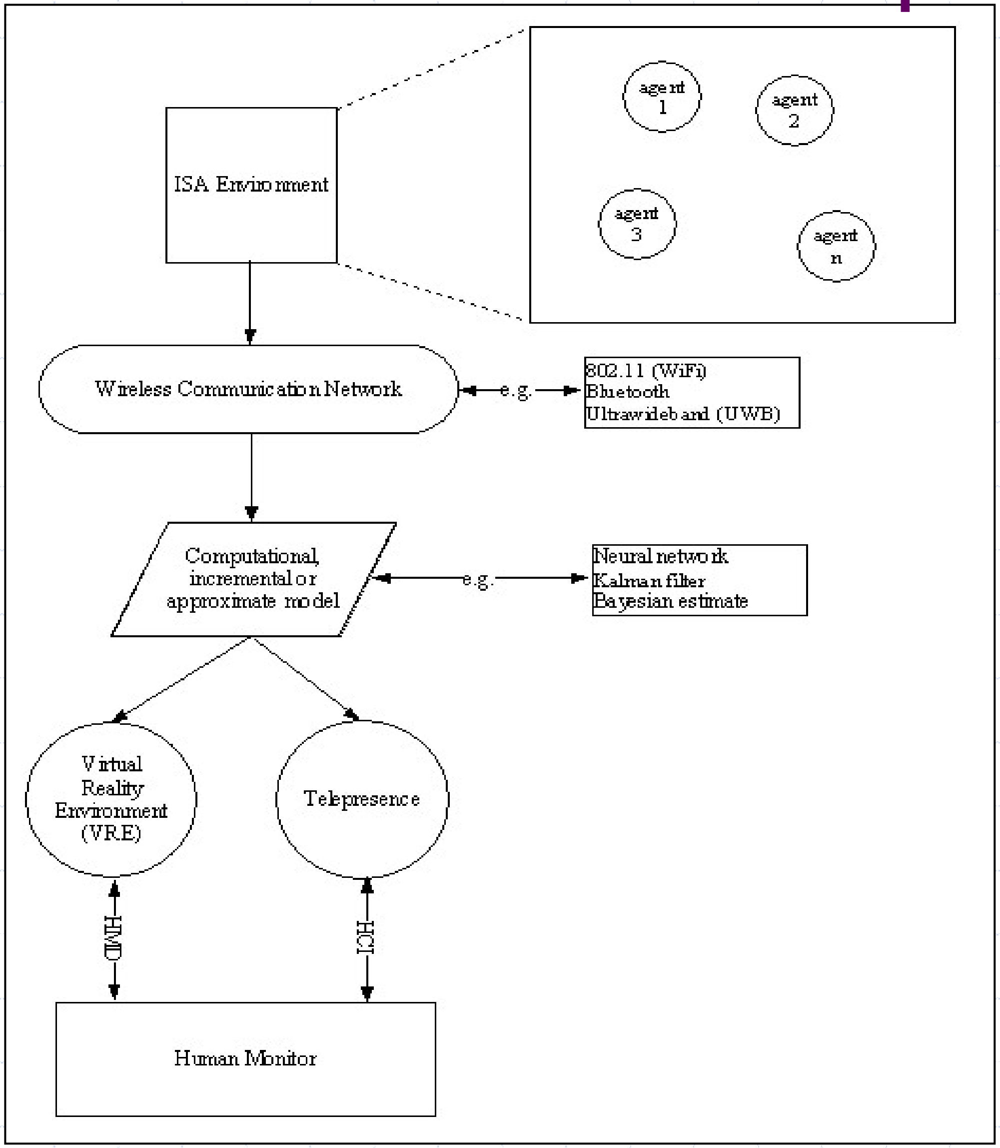


DISS is a distributed intelligent sensor system, utilized for environment monitoring. The concept involves both stationary ISAs and mobile ISAs and a wireless communication network.

Distributed wireless network of mobile and stationary intelligent sensor agents deployed in the environment. The human operator monitors the environment from a remote location using interactive virtualized reality

Figure 11. DISS architecture
Reproduced from [21]

SNET Practical Implementation #3



- ISA Environment
  - Composed of multiple robotic agents with on-board
    - Sensing capabilities
    - Computational entities
    - Communication components
  - Environment has been mapped out (structured) and can be traversed following a localized map
- Wireless Communication Network
  - Involves radio frequency technologies (commercial and academic)
    - 802.11, Bluetooth, UWB
- Computational, incremental or approximate real-world model
  - Conventionally accomplished with a computational model (i.e. Kalman filtering), but has since progressed to include biological models (i.e. neural networks) and probabilistic models (e.g. Bayesian estimates)
- Telepresence
  - Remote access to the real-world model involves perception of visual, oral, haptic and maybe in the near future olfactory sensory information
- Distributed Multimedia Virtual Reality Environment
- Human Monitor (HCI)

Figure 12. DISS flow diagram

SNET Practical Implementation #3

- DISS is composed of mISAs and sISAs, that each contain a small SNET on board. Its characteristics are as follows
  - Each agent has a global identification, but each sensor does not
  - Utilizes peer-to-peer communication between the agents and broadcast within the SNET
  - The number of agents is low, however the number of sensors is high
  - Agents and SNODEs are limited in power, memory and computation
  - Both network topologies are dynamic
  - Low-level RF modulation transceivers and proprietary wireless protocols are utilized for the agents and their on-board SNETs
  - UDP/IP is being used as the communication protocol between the agents
- We have chosen UDP/IP as the communication protocol amongst the agents, as that allows them to be queried by human users, and respond with assertions to those queries
- Micrium's µC/OS-II has been ported to the 68HCS12 microcontroller being used as the processing power of each agent
- A UDP/IP stack called lwIP [22] has also been ported to the same microcontroller
- Access points are being developed between the proprietary wireless protocols and standardized ones (e.g. ZigBee, Bluetooth and 802.11)

SNET Practical Implementation #3

- What should each mISA look like ?
- Each mISA contains a SNET composed of different types of sensors
  - Ultrasonic ranging
  - Exterior temperature
  - Light intensity
  - Smoke
  - Pressure
- Each sensor *leases* computational power, as well as communications packets, from the agent's microcontroller and transceiver
- Each agent becomes the sink node for its on-board SNET
- The sink nodes can communicate with each other or with access points (APs)
- SNODEs are composed of
  - Local sensory capabilities
  - Distributed computational entities
  - Shared communications timeslots

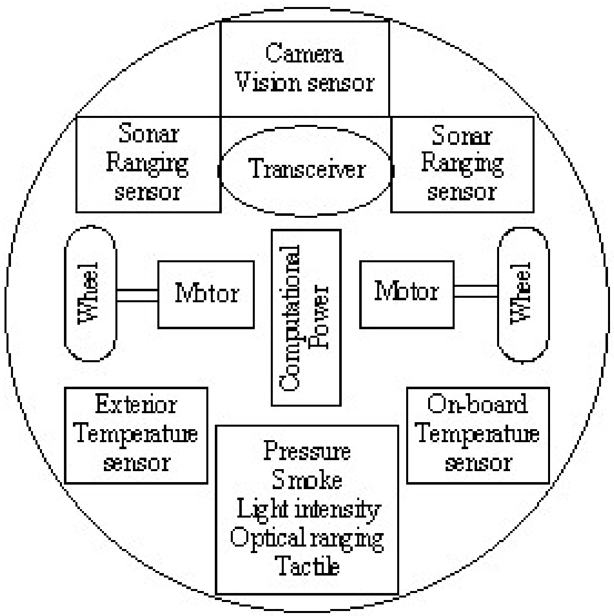
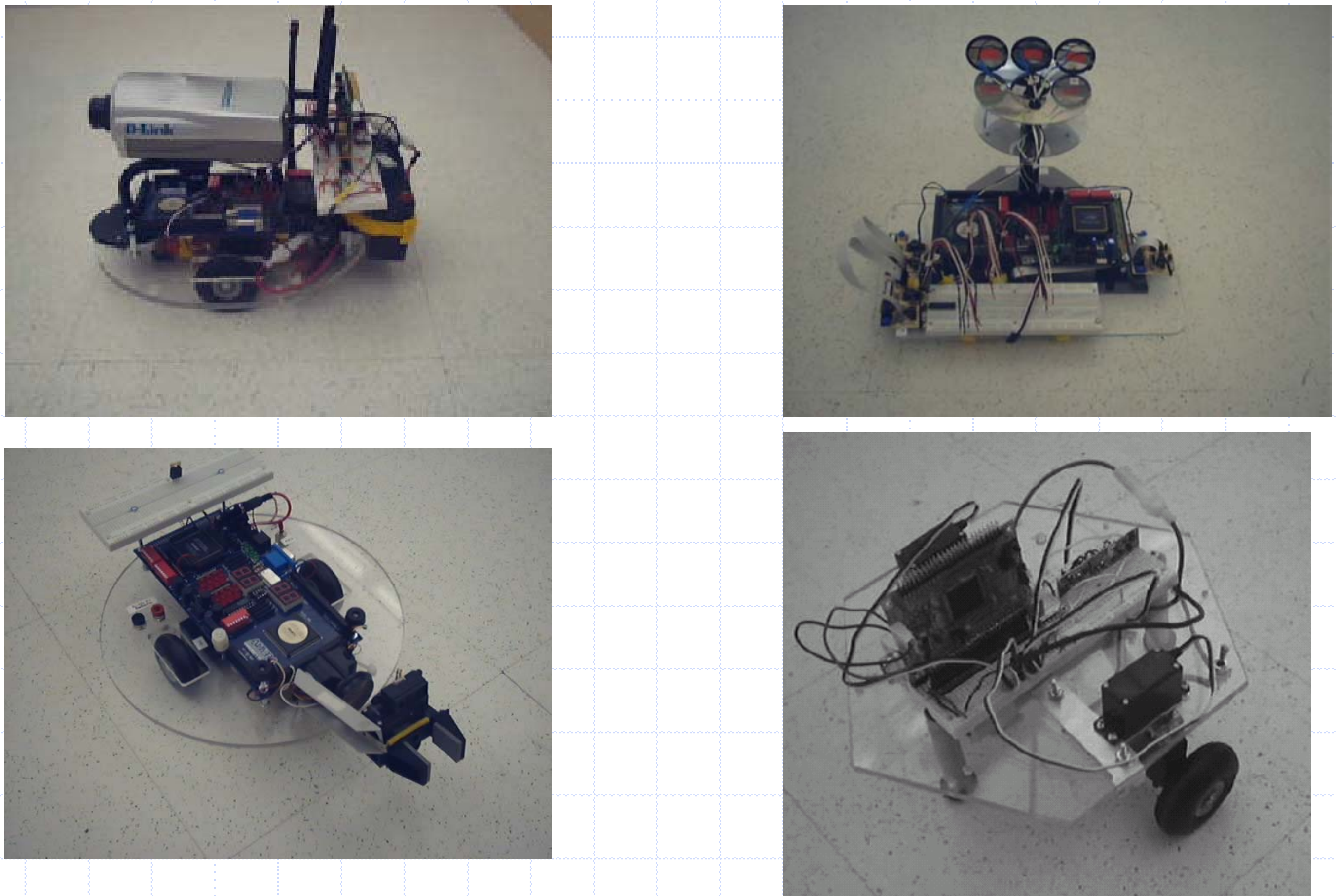


Figure 13. Ideal mISA architecture

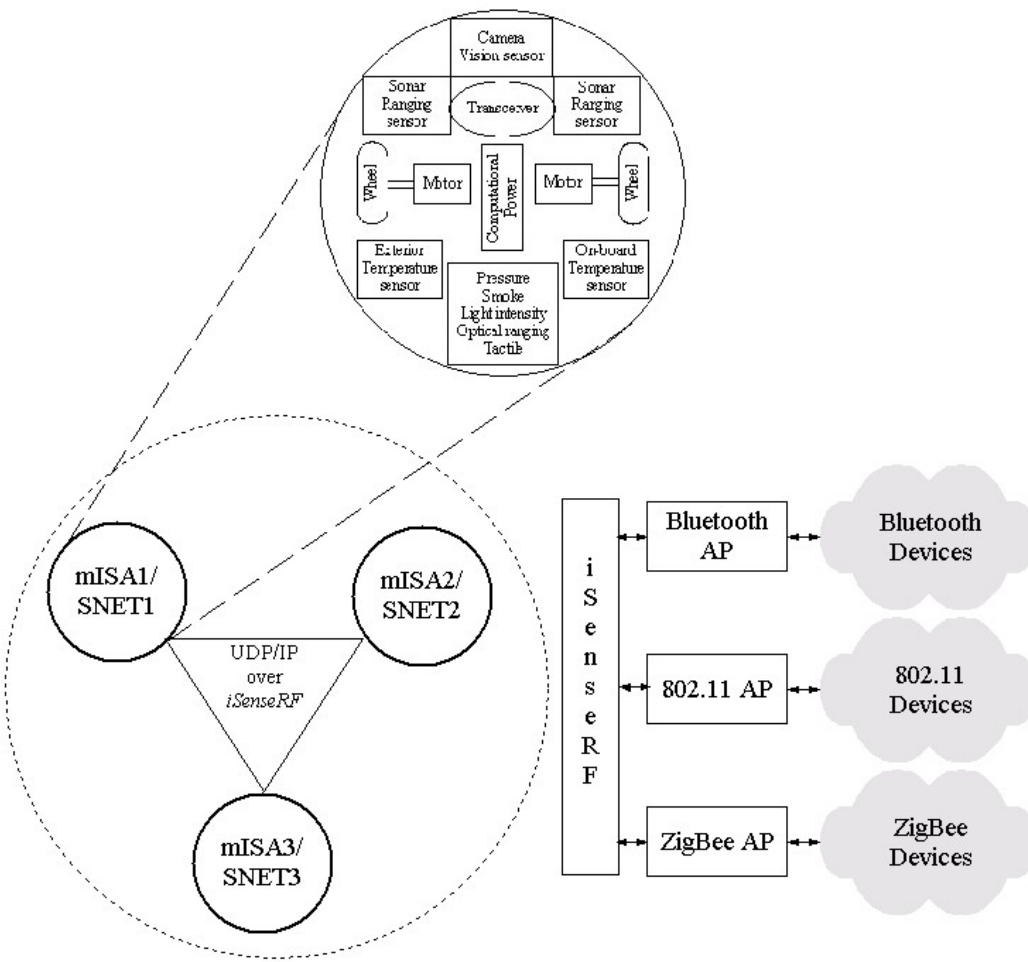
SNET Practical Implementation #3

- What does each mISA look like ?



Figures 14-17. Current mISA architectures

SNET Practical Implementation #3



Figures 18. ISA network architecture

Research Directions

- SNETs are here to stay!
- Intelligent sensor systems will be prevalent in many of the everyday tasks that are either
  - Difficult for a human to achieve (e.g. fixing a part inside a car), or
  - Mundane for a human to partake in (e.g. monitoring light intensity and closing the blinds accordingly)
- Future research directions can already be seen within the community
  - Design of tiny, low-power, low-cost modules
  - Network layer discovery and self-organization algorithms
  - Collaborative signal processing and information synthesis
  - Tasking and querying interfaces with the SNET
  - Security for protection against intrusion and spoofing
  - Reconfiguration techniques into suitable SNET configuration

Potential *Killer* Applications

- We listed a few applications at the beginning such as
  - Military (e.g. object tracking)
  - Health (e.g. vital sign monitoring)
  - Environment (e.g. natural habitat analysis)
  - Home (e.g. motion detection)
- Are the following far off ?
  - Wireless mobile SNETs can inform you of the availability of a free parking spot (maybe even allow you to reserve it ?)
  - Biological SNETs can monitor your health from within your body and can fight off viruses that may enter it
  - Nanorobotic airborne SNETs can swarm towards disaster sites and traffic jams to give their respective audiences as much visual, and overall sensory, information as possible

Market Trends

- Sensors are getting smaller in size and variable in nature
- Computing power is getting bigger and is being embedded
- Communications bandwidth is getting higher and transceivers are getting smaller
- Look for the following soon
  - Negligible weight, dust particle size
  - Integrated sensing/processing/communication
  - Solar-powered modules
  - Completely peer-to-peer topologies
  - SNODEs will be like *Oxygen* [23] (MIT ubicomp project)
  - SNETs will be embedded into the very fabric of our lives that they will inherently disappear!
- What about mobilizers and actuators ?
  - Can you imagine smart dust particles that can mobilize and actuate upon their environment ?
  - *In approximately 5 years, on a PCB somewhere, after sensing and synthesizing (network concensus) that a micrometer-wide pin has been broken, a SNET self-organizes logically and physically and proceeds to solder the pin back to the chip!*

Conclusions

- SNETs provide flexibility, fault-tolerance, high sensing fidelity, low-cost and rapid deployment
- Soon, we will be interacting with smart garments, smart appliances, smart sensor networks, and even smart floor tiles!
- However, we must keep in mind that we have to
  - Fall back onto standards, when available
  - Share information about our work
  - Think passionately but design cautiously!

- Lots of work ahead of us!
- Lost of fun ahead of us!

Work + Fun = Research

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Contact Information

Questions ?

Comments ?

- Rami Abielmona
- SITE – Ph.D. Candidate
- SMRLab Research Assistant
- http://www.site.uottawa.ca/~rabielmo
- rabielmo@site.uottawa.ca